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ELECTRICAL DAMPING OF VFD INDUCED TORSIONAL TORQUE PULSATIONS IN A LCI DRIVEN COMPRESSOR DRIVE TRAIN

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ABSTRACT

Variable-frequency drives (VFDs) are being increasingly employed in oil and gas (O&G) applications due to their better efficiency, reliability and process control when compared to conventional drives. In comparison with conventional industrial gas turbines, electrical drives result in at least 7 to 10 more production days per year. For high power applications ranging from 1 MW up to 100 MW medium-voltage (MV) VFDs are the preferred solution. Depending on the required power, different types of VFDs are available in the market. Due to their working principle the VFDs inject harmonic and interharmonic currents to the electrical motor. The non-

perfect sinusoidal current/voltage waveforms of the VFDs produce pulsating torque components in addition to constant torque. The torsional characteristics of a drive train involving turbo compressors play an important role in amplifying or damping the harmonics and interharmonic air-gap torque components injected by a VFD. The injected pulsating torque components and their amplitudes depend on the type of the drive used. The Load Commutated Inverter (LCI) is a commonly used VFD for higher power applications (>30 MW).

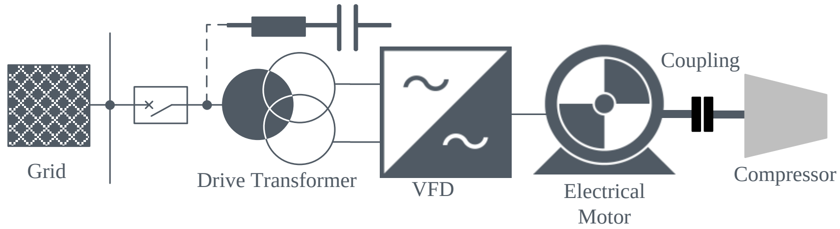

Figure 1: VFD driven compressor system

This is a current DC-Link based drive, perfectly suitable for such high power compressor applications. LCI drives produce operating speed dependent interharmonic air-gap torque components (pulsating torque components). The interharmonic pulsating torque excitations of the LCI drives are seen as a major limitation of such drives in regard to the torsional characteristics. The interharmonic behavior of a LCI drive will be explained together with the typical torsional characteristics of a typical drive train involving turbo compressors. The currently employed methods by turbomachinery engineers to overcome the interharmonic problems will be summarized. This paper then proposes a novel concept using active electrical damping, to eliminate the interharmonic torque components of a LCI drive. The results of employing this active damping technique in a real plant are shown to demonstrate the effectiveness of the proposed damping concept.

INTRODUCTION

Torsional characteristics of turbo compressor drive train:

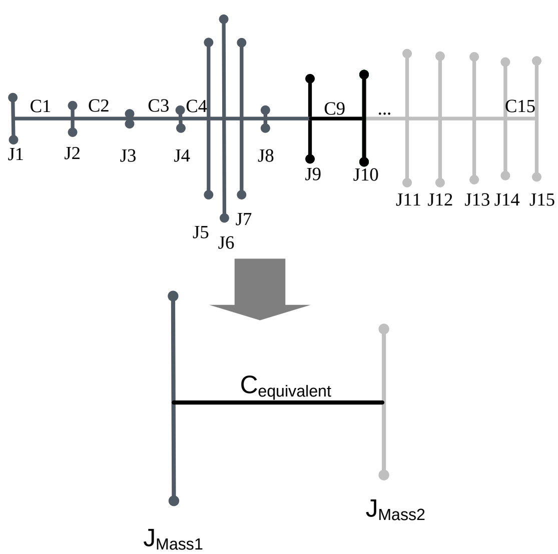

Figure 2: Mechanical model of motor, coupling and compressor

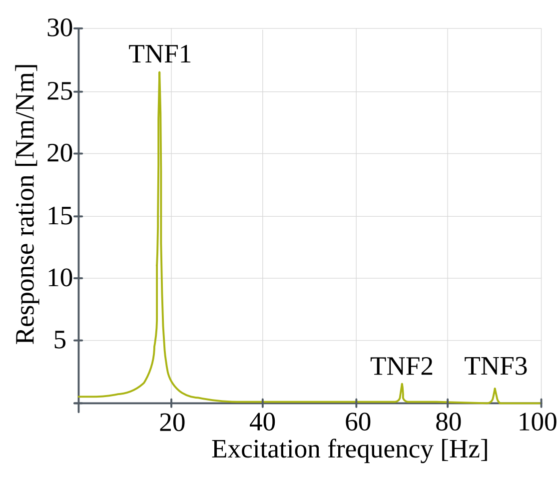

Figure 3: Typical torsional response of turbo-compressor drive train

Figure 1 shows a simplified representation of typical Variable Speed Drive System (VSDS) employing electrical drives (VFDs – Variable Frequency Drives) driving a compressor. Independent of the type of VSD used the mechanical torsional characteristics of the drive train comprising of driven compressor, electrical motor, coupling and gear if any can be analyzed using a multiple mass system as shown in Figure 2. This can be further simplified into a two mass model also shown in Figure 2. This model is sufficient to calculate the 1st Torsional Natural Frequency (TNF) of the drive train. The typical torsional response of such a drive train is shown in Figure 3. Normally for a drive train with one motor driving a compressor, only the first TNF is critical. This is due to the fact that amplification factors of the higher TNFs are negligible. But criticality of the TNFs also depends on the mode shapes. Also it can be seen from Figure 3, that the TNF are very sharp. The amplification factors normally vary with the compressor manufacturers. In case if the motor has to drive more than one compressor or the electrical motor is used as a starter-helper together with a gas turbine, due to the three mass system more than one TNFs can become critical.

Variable Frequency Drives

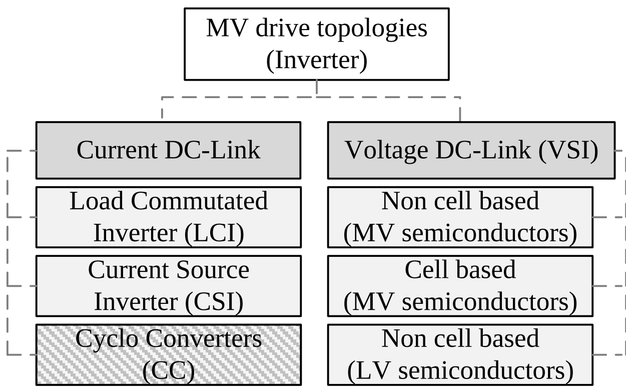

Figure 4: Overview of medium-voltage drive topologies

Depending on the power, speed and torque requirement different types of VFDs are available in the market. An overview of the main VFD types is provided in Figure 4. The LCI drives are employed for high power applications from 30 MW onwards. Due to recent development in the field of power electronics the VSI drives are currently being considered also for higher powers > 30 MW. One of the main advantages of VSI drives is the comparatively smaller pulsating torque amplitudes over the LCI drives. But as can be seen in Figure 4 there are many different topologies of VSI drives available in the market. Hence a general statement on pulsating torque characteristics of VSI drive is not possible. This is due to the fact, pulsating air-gap torque produced by a VSI drive depends on the topology and also the control method used by the drive.
The other advantage of a VSI drive is its line side characteristics, input power factor and current harmonics. VSI drives with diode rectifiers operate with a line side power factor > 0.95 and typically no additional harmonic filters or power factor compensation devices are required. LCI drives inherently require power factor compensation and harmonic filters to limit the input current harmonics and reactive power demand.
LCI drives are proven technology for compressor applications and are simple and robust compared to VSI drives. If the above mentioned two issues (pulsating torque and input harmonics) are considered and the required measures are taken during the initial planning phase, LCI is still the best drive for high power compressor applications. The proposed active damping of the characteristic pulsating torque will eliminate at least one major issue with the LCI drive.

LCI drive system:

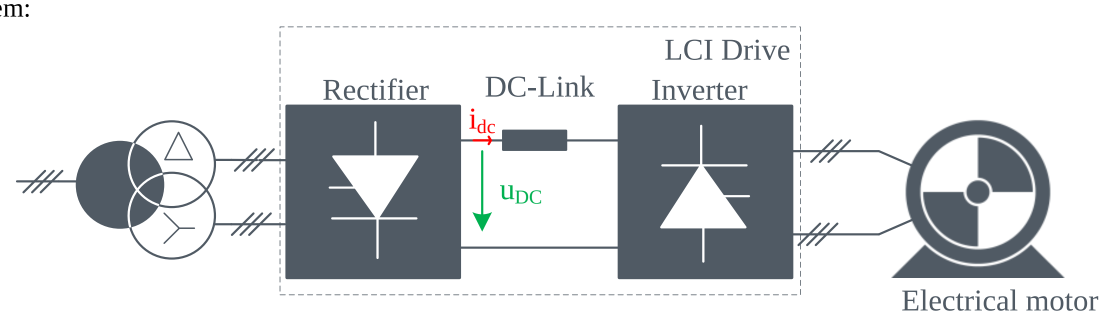

Figure 5: Simplified circuit diagram of a 12/12 pulse LCI drive system

An LCI drive (Beuermann, M et al. 2008, Wu, B et al. 2017) for continuous operation is normally designed as 12/12 pulse configuration as shown in Figure 5. It has a 12 pulse rectifier to convert the three phase AC grid voltage to intermediate DC current. The 12 pulse inverter converts the intermediate DC into three phase AC with variable frequency corresponding to the compressor speed. To achieve the 12/12 pulse configuration in addition to the LCI drive a three winding transformer with two 30° phase shifted secondary winding systems and a motor with two three phase winding systems with 30° phase shift are required.

INTERHARMONIC AIR-GAP TORQUE EXCITATIONS OF LCI DRIVES

Interharmonic air-gap torque generation in a LCI drive (Huetten, V et al. 2008)

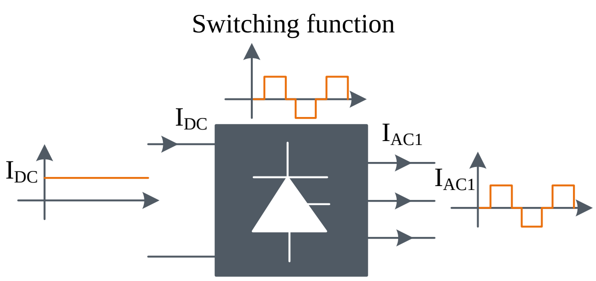

Figure 6: DC-Link and motor current waveforms for $L_{DC} = \infty$

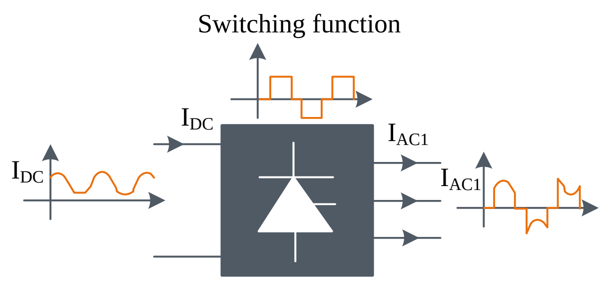

Figure 7: DC-Link and motor current waveforms for $L_{DC} \neq \infty$

The LCI drive first converts the AC voltage into an intermediate DC current. In the DC-Link between the rectifier and the inverter a reactor is used to smooth the rectified DC current. If this reactor has an infinite inductance ($L_{DC} = \infty$) which is possible only in ideal conditions, no current ripple from rectification will be seen in the DC current. This DC currents will be switched ON and OFF by the thyristors (semiconductor devices used in LCI drive) in the inverter to create the output motor sinusoidal current. Due to this switching, the output current contains harmonics in them. Harmonics are integer multiples of the fundamental sinusoidal frequency, and hence are always higher than the fundamental frequency. But in reality the DC-link inductance is an absolute value, and hence the DC-link current in not ideally constant but will have harmonics from the rectifier. These are integer multiples of the line frequency. This DC current will be modulated to the motor side. Now the motor current has not only harmonics due to the inverter switching but also the combination of integer multiples of line frequency and integer multiple of motor frequency. These components are not exactly integer multiples of the motor frequency, and hence are called interharmonics. These above two cases have been shown in Figure 6 and Figure 7. These non-sinusoidal currents with harmonic and interharmonic components will create corresponding frequency components in the air-gap torque. Figure 8 and Figure 9 show the typical motor three phase current and torque waveforms. The harmonic and interharmonic air-gap torque components can be seen in Figure 10. The relation between the frequency components in motor current and motor air-gap torque is

$$f_{h\_Torque} = f_{h\_Current} \pm f_{1\_Motor} \text{ Hz} \quad (1)$$

$$f_{1\_Motor} = \frac{n_{Motor}}{60} \cdot N_{PolePairs} \quad (2)$$

The harmonics and interharmonics air-gap torque components are thus function of the grid supply frequency (50/60 Hz) and the operating motor frequency. This can be clearly seen in Figure 10. There are integer multiples of the motor (f_{motor}) and line (f_{line}) frequencies. In addition to them there are also the multiples of the difference between these two frequencies (f_{line} -f_{motor}). In general with in the operating speed range (typically 70% to 105% or rated speed), the harmonics of motor and line frequencies are not critical even with higher amplitudes. This is because;

a. the mechanical drive train has a very high damping coefficient for these higher frequencies
b. Critical TNFs are typically less than 30 Hz.

Hence only the interharmonic components, which are multiples of the difference frequency (f_{line} -f_{motor}) may excite the low TNFs within the operating speed rang. But the magnitude of interharmonic air-gap torque excitations is much smaller compared to that of the harmonic components.

The air-gap torque excitation frequencies are thus a function of the operating speed of compressor. This is represented through a Campbell diagram.

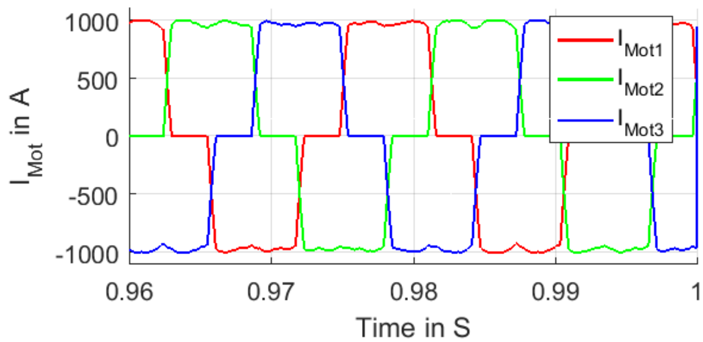

Figure 8: Motor current waveform of a 12/12 pulse LCI drive (one winding system current has been shown)

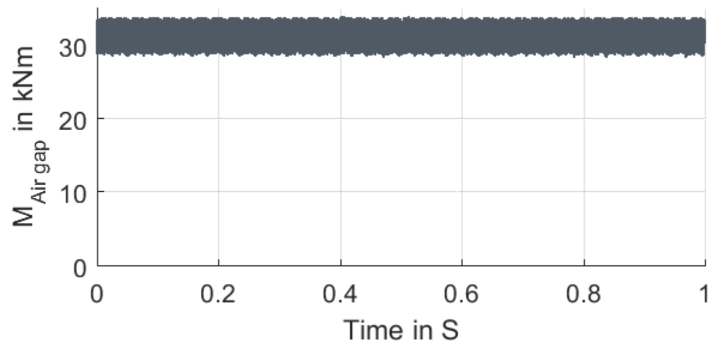

Figure 9: Motor air-gap torque waveform of a 12/12 pulse LCI drive

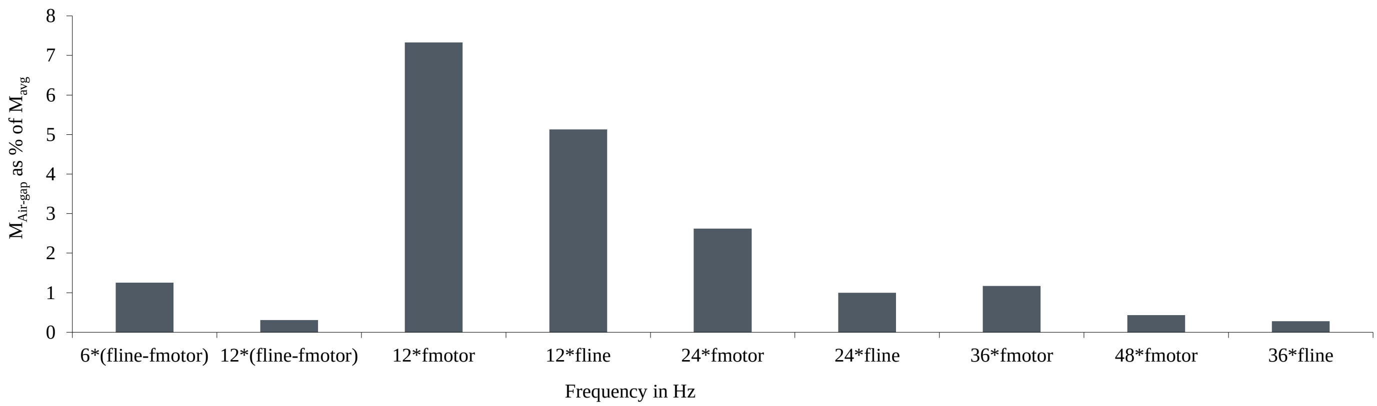

Figure 10: Typical frequency spectrum of air-gap torque produced by a 12/12 pulse LCI drive system

Campbell diagram

A Campbell diagram is an important tool which acts as a first link between the electrical and mechanical engineers. The excitations expected from an electrical drive system and the critical torsional resonance frequencies are put in one diagram to visualize the torsional situation.

Figure 11 shows the Campbell diagram of a 12/12 pulse LCI drive for the parameters shown in Table 1. The harmonic components in the air-gap torque increase linearly with the motor operating speed. The interharmonic components are the "V"s seen in the Campbell diagram. The operating speed range is indicated in the speed range. The x-axis of the diagram is the motor/compressor speed in rpm. The y-axis represents the excitation frequencies of the driver. No information on the magnitude of the air-gap torque excitations and the amplification factor at TNF are available in the Campbell diagram. A torsional analysis of the mechanical drive train will result in the torsional natural frequencies as shown in Figure 2 and Figure 3. This TNF(s) is also plotted in the Campbell diagram.

Table 1: Electrical drive system parameters considered for the Campbell diagram

Parameters	Values	
Line frequency	60	Hz
Motor rated frequency	60	Hz
Number of pole pairs	1	pu
Min. operating speed p. u.	0.7	pu
Max. operating speed p. u.	1.05	Pu
Number of pole pairs	1	
1st Torsional Natural Frequency (TNF)	20	Hz

Interpretation of Campbell diagram

With the drive system specific excitation frequencies and the TNFs put in the Campbell diagram, any intersections of the TNF with excitation frequencies within the marked operating speed range represent the operating speed set points at which the TNF will get excited by the air-gap interharmonic pulsating torques. This does not mean to be critical as the magnitudes of the excitations torque and the amplification/damping factor at the TNFs are not yet known. But this gives us, the potential speed points where further investigations are required.

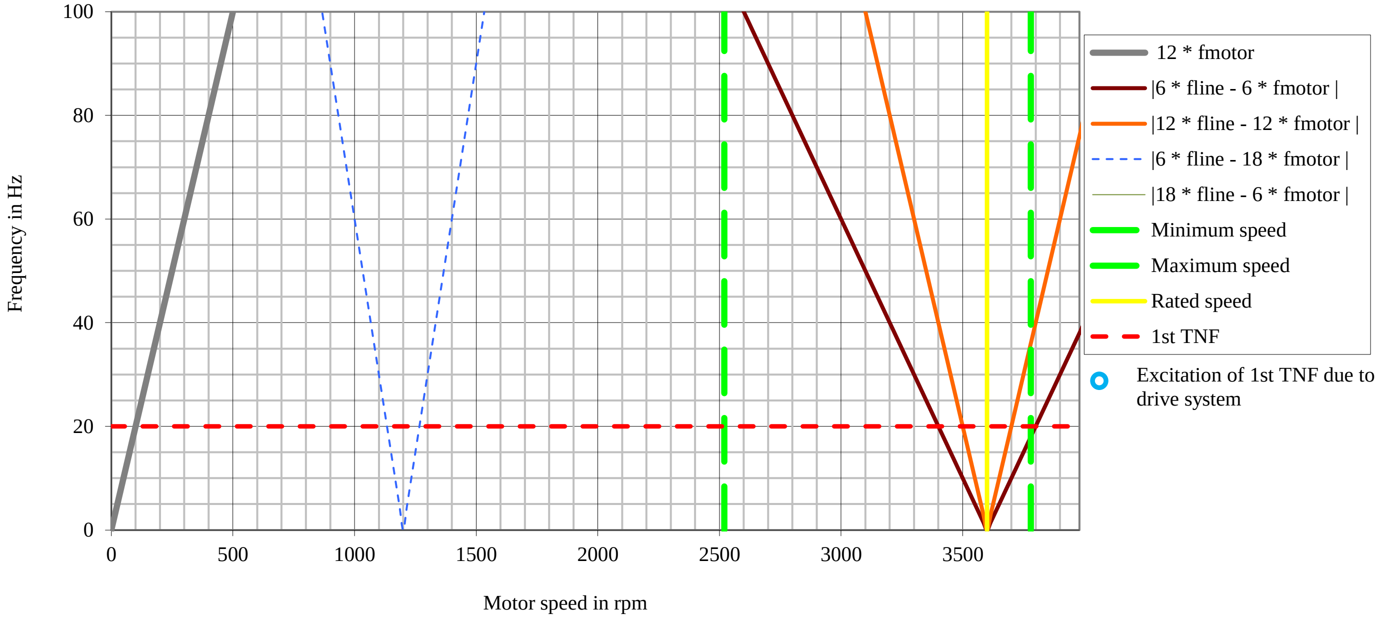

Figure 11: Campbell diagram showing the air-gap torque excitation frequencies for a 12/12 pulse LCI drive with a 2 pole motor with a TNF shown as an example.

If intersections of the TNFs with LCI drive excitation frequencies are identified, the following investigations may give a clear picture; check the drive train integrity by using a drive supplier independent worst case value of 2 % for the excitations. This can be performed by the OEMs without any input from drive suppliers for the LCI drive. And if the drive train integrity is intact with the worst case excitation amplitudes then the risks of failures due to torsional problems are very low. If the stress levels on the drive train components are higher than the threshold limits for worst case excitation magnitude (indicative value of 2% independent of the interharmonic frequency), detailed analysis should be performed by the drive suppliers and the OEMs. The drive suppliers should calculate the project specific air-gap interharmonic torque excitations. This can be done using detailed and realistic simulations of the electrical system. These values can be used to check the drive train integrity with project specific amplification/damping factor at the TNFs. It should be noted that, determining the exact damping at TNF may be very complex (Wachel et al., 1995, Corbo et al., 1996) and is not in the scope of this paper. If these investigations results in the stress on components exceeding the threshold values, additional measures may be required to reduce or eliminate the risks.

Several techniques are available currently and have been well-documented in past. They are summarized below;

A. Design the electrical drive system, to avoid any excitation of the critical Torsional Natural Frequencies (TNF) within the operating speed range (Huetten, V et al. 2013). This can be done by
    a. choosing optimum number of pole pairs
    b. choosing the optimum input pulse number 12 pulse or 24 pulse
B. Mechanically re-designing the components to withstand the stress due to the interharmonic pulsating torque injected by the VFD
    a. Changing the stiffness of the coupling (Hudson et al. 1992)
C. Skipping a particular operating speed range to avoid excitation of the TNFs (Huetten, V et al. 2013**)**.
D. Electrical damping (Naldi, L et al. 2007) – in past some electrical damping techniques have been presented, but these were mostly compressor specific and require knowledge about drive train torsional characteristics

Each of the above methods has their pros and cons. The overall practice explained above is summarized in form of a flow chart in Figure 12. The key aspect of the recommended practice is, to have a good collaboration between the electrical and mechanical engineers. This practice can also be followed for projects not involving LCI drives and independent of the involved OEMs.

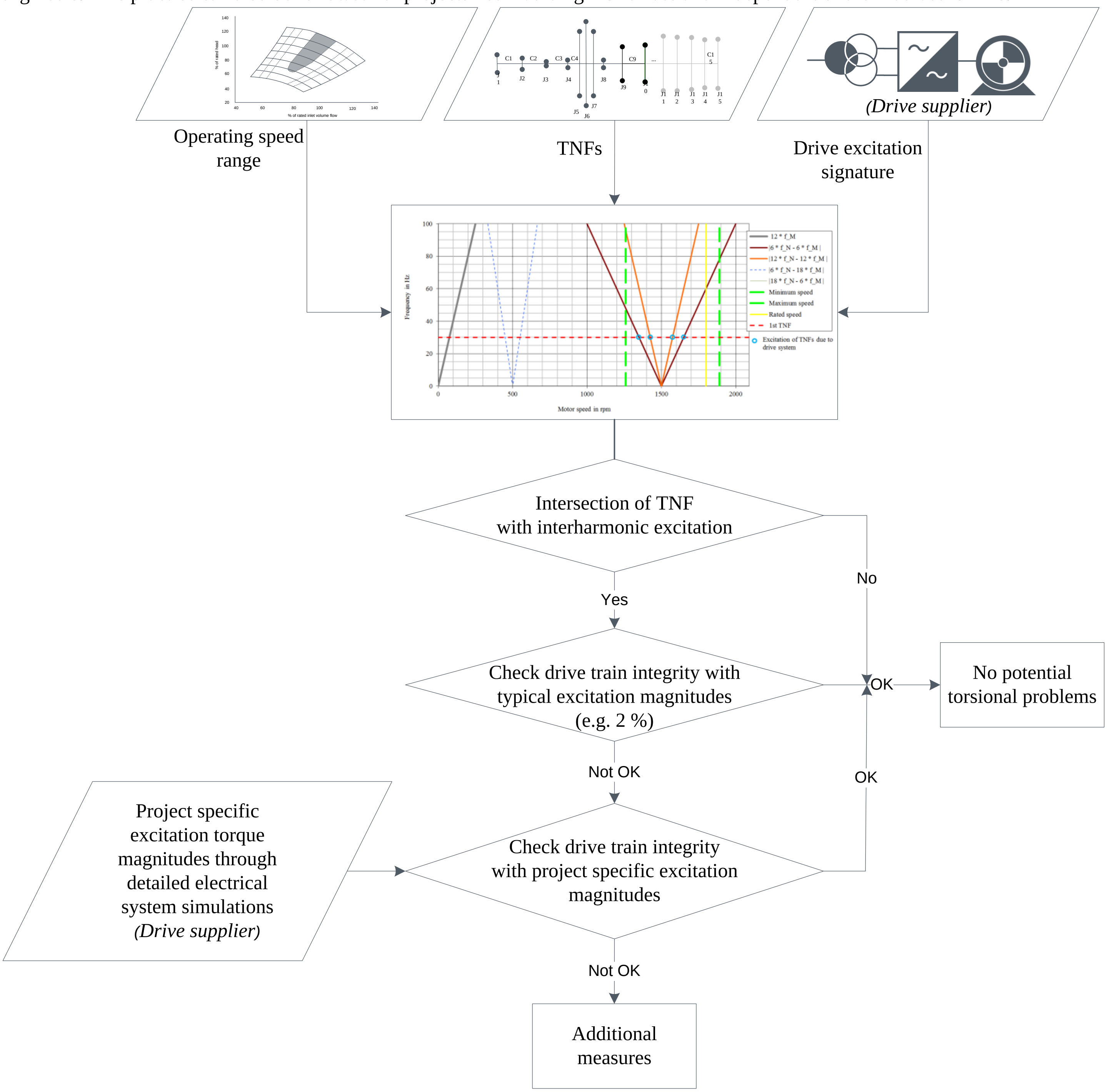

Figure 12: Recommended practice before equipment procurement for analyzing and reducing the risk of torsional problems in a VFD driven drive train with a turbo-compressor

Table 2: Comparison of the existing interharmonic torque reduction/elimination methods

Criteria	Measure A	Measure B	Measure C	Measure D
Short description	Pre design phase: The compressor drive train and the electrical drive train are designed to avoid any intersections of interharmonic torque excitations with the TNFs. This is a risk free approach as it does not take the amplitude of excitations or the damping factor at the TNFs into consideration. Thus the uncertainties in the calculation of these values are not harmful anymore. This method cannot be used as a corrective measure in case of torsional problems.	Pre design phase: If this method is considered during the pre-design phase, the mechanical drive train components are designed • to withstand the stress due to the torsional oscillations • to influence the TNF • to increase the damping factor at TNFs As corrective measure: • to shift the TNF • to add damping For e.g., this can be done using different type of couplings.	As corrective measure: This method is predominantly used as a corrective measure if all other measures do not help. Skip speed ranges are programmed in the VFD at which the drive will automatically accelerate to the set speed points. This avoids the continuous operation at speed points where the TNFs will be excited by the drive system.	As corrective measure: This method is used to damp the TNF. The torque is measured at the critical part of the shaft and will be fed to the VFD control or additional control equipment. Special damping control software has to be implemented. The software has to be adjusted due to the train and motor parameters. Alternatively to the torque measurement a observer of the motor and train can be used. The observer software needs exact train and motor parameters.
Pre requisite	• Exact information of TNFs • Excitation signature of drive system	• Exact information of TNFs • Exact damping coefficient at TNFs • Excitation signature of drive system • Amplitudes of the excitations	• Exact information of TNFs • Excitation signature of drive system	• Exact information of TNFs • Excitation signature of drive system
Advantages	• Risk free design, tolerances in calculation of damping factor is not a problem • No torsional issues expected	• Limited risk if accurate calculations are possible and are performed during design phase • Can be the solution if all other measures do not help	• Can be the solution if all other measures do not help • Easy realization through VFD software	• Can be uses as a corrective measure • All disturbances on the train can be damped
Disadvantages	• Depending on the, compressor speed drive system may need higher cost • Cannot be used as a corrective measure for drive trains not designed accordingly	• More experience and expertise required • Tolerances in calculation of damping factor and excitation amplitudes are critical • If used as corrective measure, require longer down time as it requires exchange of mechanical components (hardware changes)	• No optimum in the view of process engineers • May get complex if more drive trains are involved in the plant • Not an economical option at least for process engineers	• Need extensive knowledge of compressors drive train • the methods available in market requires additional torque sensors or an exact observer software of the motor and train • OEM specific • Typically seen only as a corrective measure

ELECTRICAL DAMPING OF LCI DRIVE CRITICAL INDUCED INTERHARMONIC AIR-GAP TORQUES

The proposed novel active damping method uses VFD control software to eliminate the LCI drive specific air-gap torque excitations at selected operating speed ranges. This does not require any additional sensors or other control hardware. The information required from the compressor drive train is the TNFs and the bandwidth around them. The principle of the proposed active damping can be explained through the following Campbell diagram. With the new control feature the LCI drive does not produce any air-gap torque excitations around the specified TNFs.

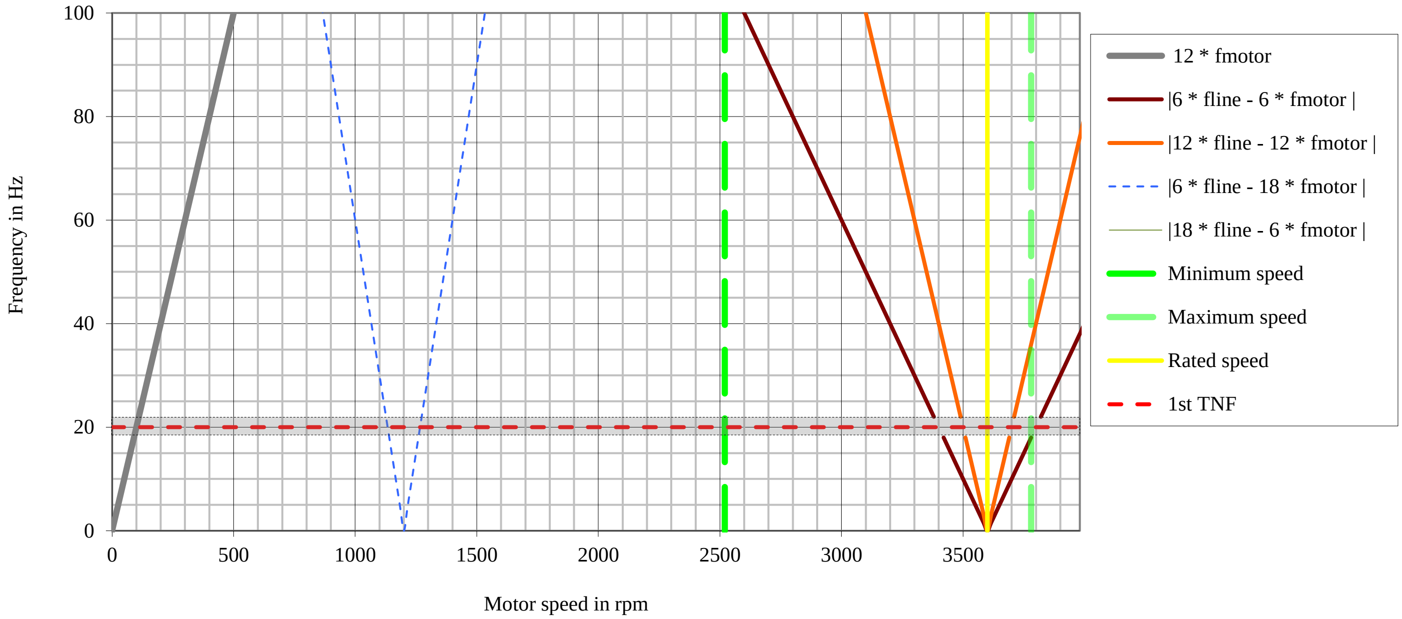

Figure 13: Effect of active damping in the LCI drive on the Campbell diagram

Implementation of the active damping in VFD control

In addition to the conventional speed and inner current loop control in a LCI drive, interharmonic torque control algorithm is added. This part identifies the relevant interharmonic component which may excite the specified critical TNF, and control this particular frequency component to zero, thus eliminating the relevant interharmonic torque excitations. A simplified block diagram of the interharmonic component controller is shown in Figure 14.

The additional control algorithm identifies the critical interharmonic component within the specified frequency band (ΔF) around the critical TNF for the operating speed. This can be any one of the two LCI specific interharmonic components $6*|f_{line} – f_{motor}|$ and the $12*|f_{line} - f_{motor}|$. Even though theoretically many more interharmonic components are possible, their amplitudes are very less. Hence only the above mentioned two interharmonic components are only damped actively. The amplitude of this relevant interharmonic component will be extracted from the estimated air-gap torque. This component will be compensated by adjusting the motor side inverter firing angle α_{motor}. The thyristors in the inverter (motor sides) will be turned on at this firing angle $\alpha_{motor.}$ One electrical period (20 ms at 50 Hz motor frequency) corresponds to 360°. This control algorithm will be active only if there is an interharmonic component within the specified frequency band (ΔF) around the TNF. The accuracy of the actual value measurements is very important for this principle. The change in the motor side firing angle is performed in a way it does not affect the normal performance of the drive or lead to any commutation failures. The following additional inputs are required,

1. TNFs, up to two different TNFs can be input → with this we can apply this for drive trains involving two compressors driving by one electrical motor or also for electrical motor used as a starter helper.
2. The frequency bandwidth of around the specified TNFs where the interharmonic air-gap torque excitations have to be eliminated.

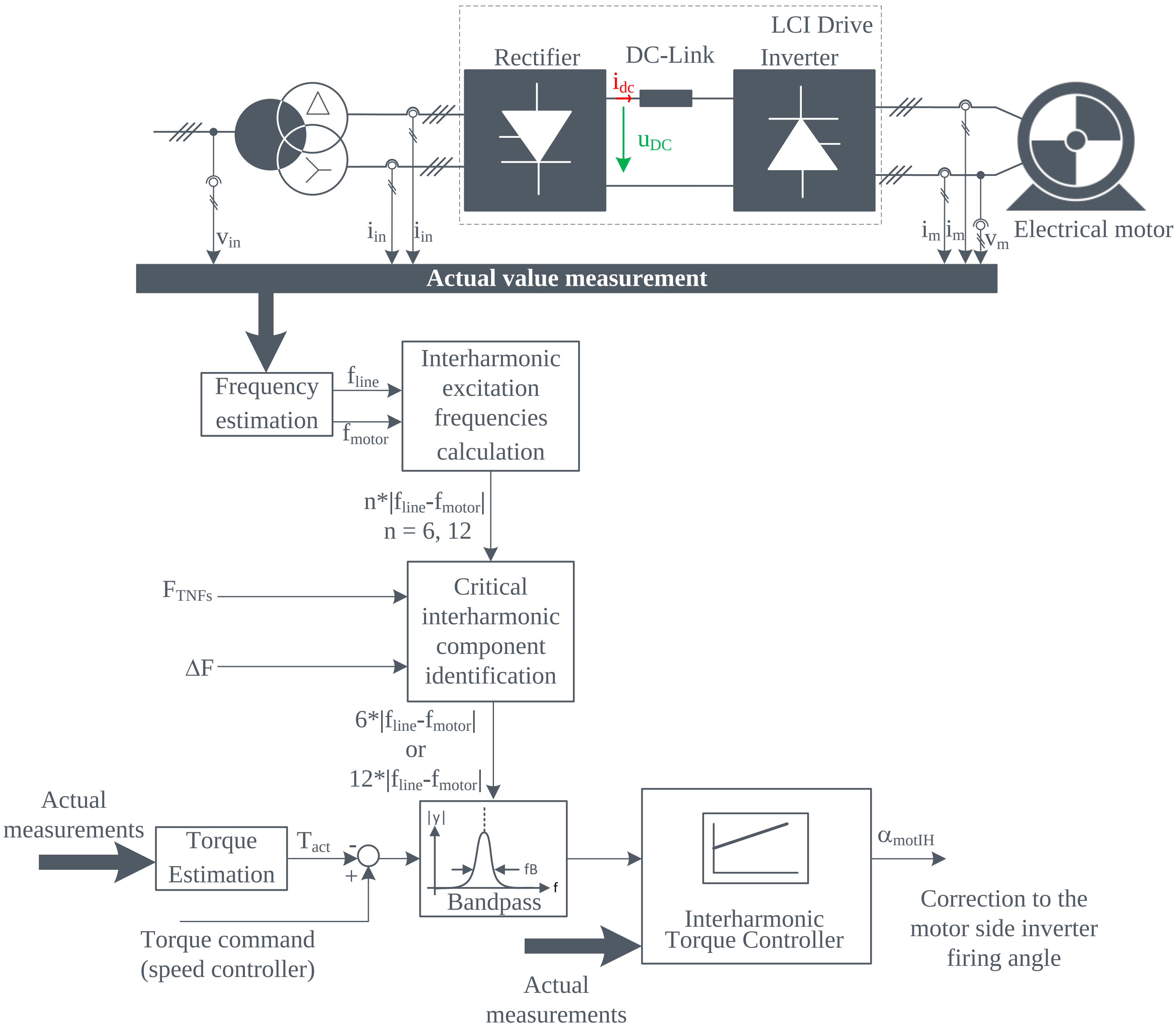

Figure 14: Interharmonic torque component control block diagram for LCI drive.

VALIDATION OF THE PROPOSED ELECTRICAL DAMPING THROUGH MEASUREMENTS

The proposed novel active interharmonic torque damping through VFD control has been validated extensively through drive system simulations. Once good results were obtained, it was implemented in a real plant.

Plant configuration

Figure 15 shows the drive system configuration of the plant where the proposed damping algorithm was tested.

For this plant configuration, the critical TNF of the drive train will get excited through the LCI injected air-gap interharmonic torque excitations within the operating speed range. This is shown in Figure 16. The critical TNF of this drive train was measured at 24.9 Hz. The intersection points are marked as A. B and C in the Campbell diagram shown in Figure 16.

Table 3: Speeds at which the TNF gets excited.

A	B	C
2877 rpm	3124 rpm	3248 rpm

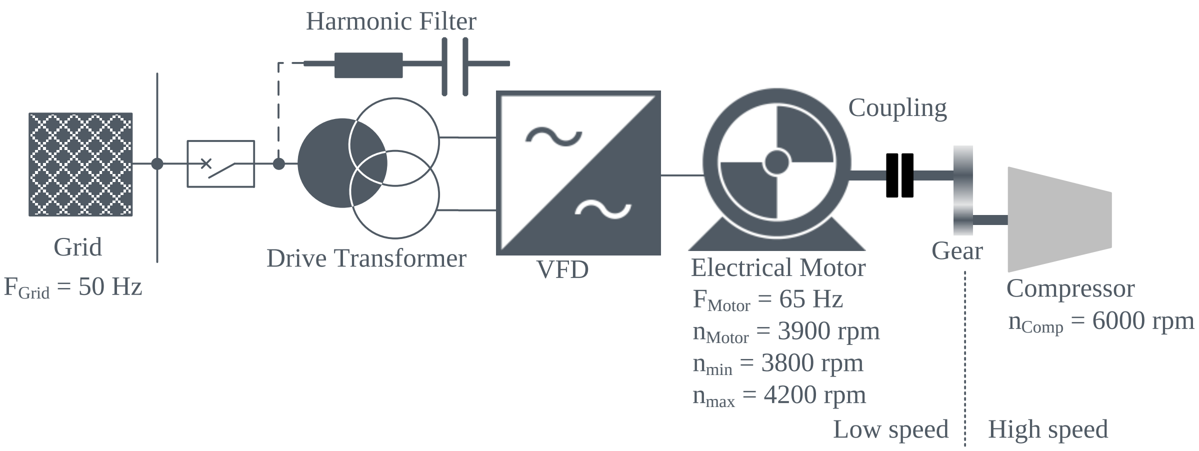

Figure 15: Plant drive system configuration where the active damping has been tested.

Strain gauges fastened on the intermediate shaft (between motor and gear) were used to measure the torsional torque pulsations. Measurements were performed without the proposed damping technique and by activating it.

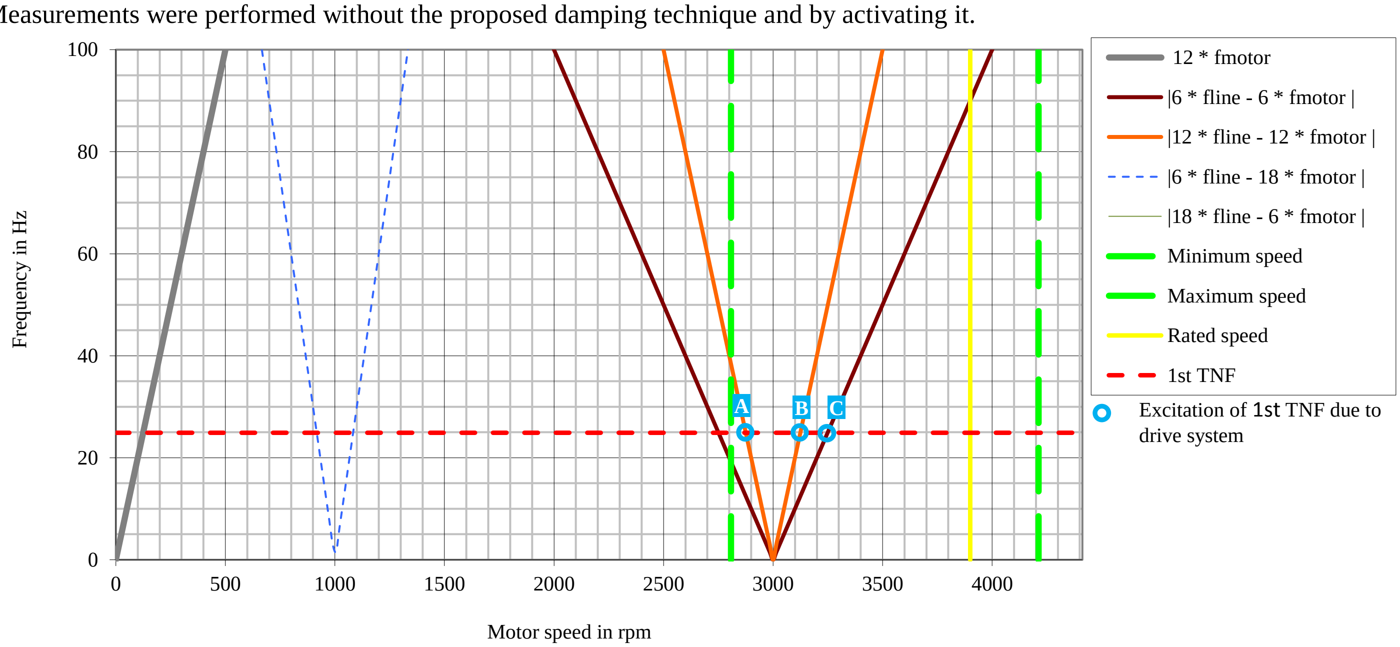

Figure 16: Campbell diagram of the considered LCI drive system.

Measurement results:
As expected the measurement without active damping shows (Figure 17) the expected interharmonic torque pulsations exactly at the expected operating speeds. These are marked as A, B, and C in the measurements (Figure 17).
The TNF frequency is set as input for the interharmonic damping controller, and the measurements were repeated with the active damping. Figure 18 shows clearly the effect of the active interharmonic damping on reduction of the pulsating torque at speed points A, B and C. The waterfall diagrams (Figure 19 and Figure 20) with and without the active damping clearly demonstrates the

interharmonic torque suppression as explained and shown in Figure 13.

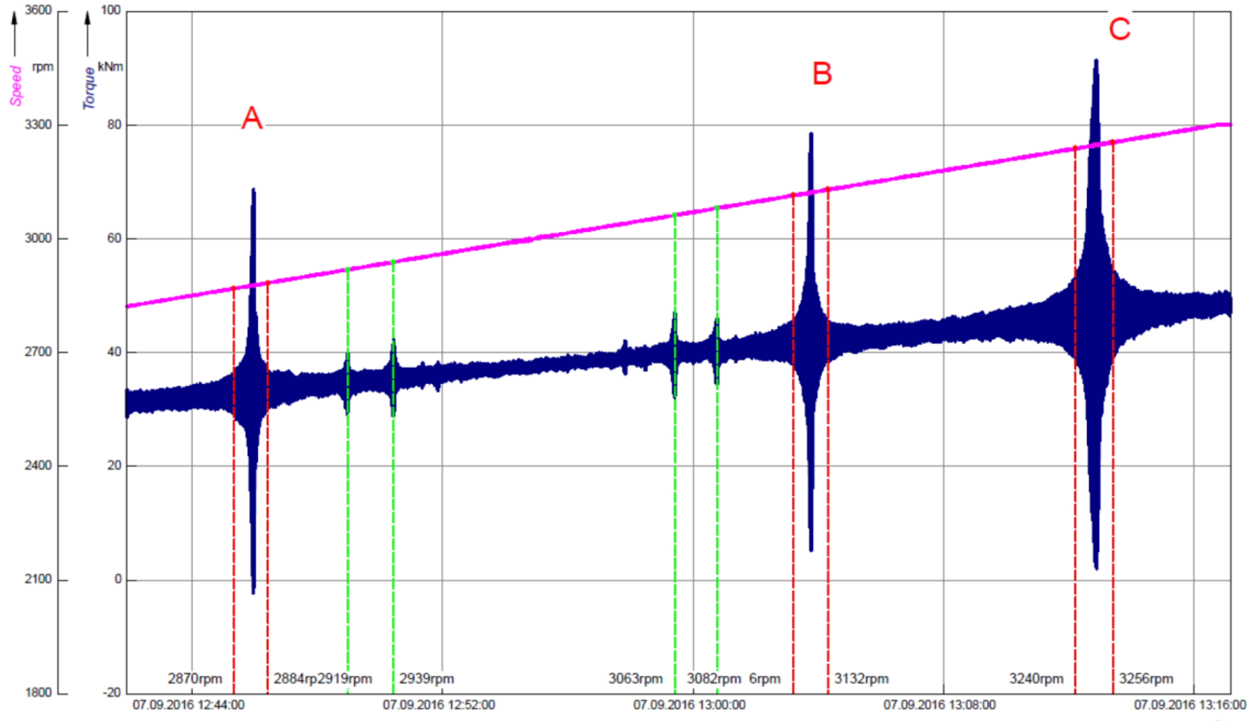

Figure 17: Measured speed and torque at the low speed side without active interharmonic damping

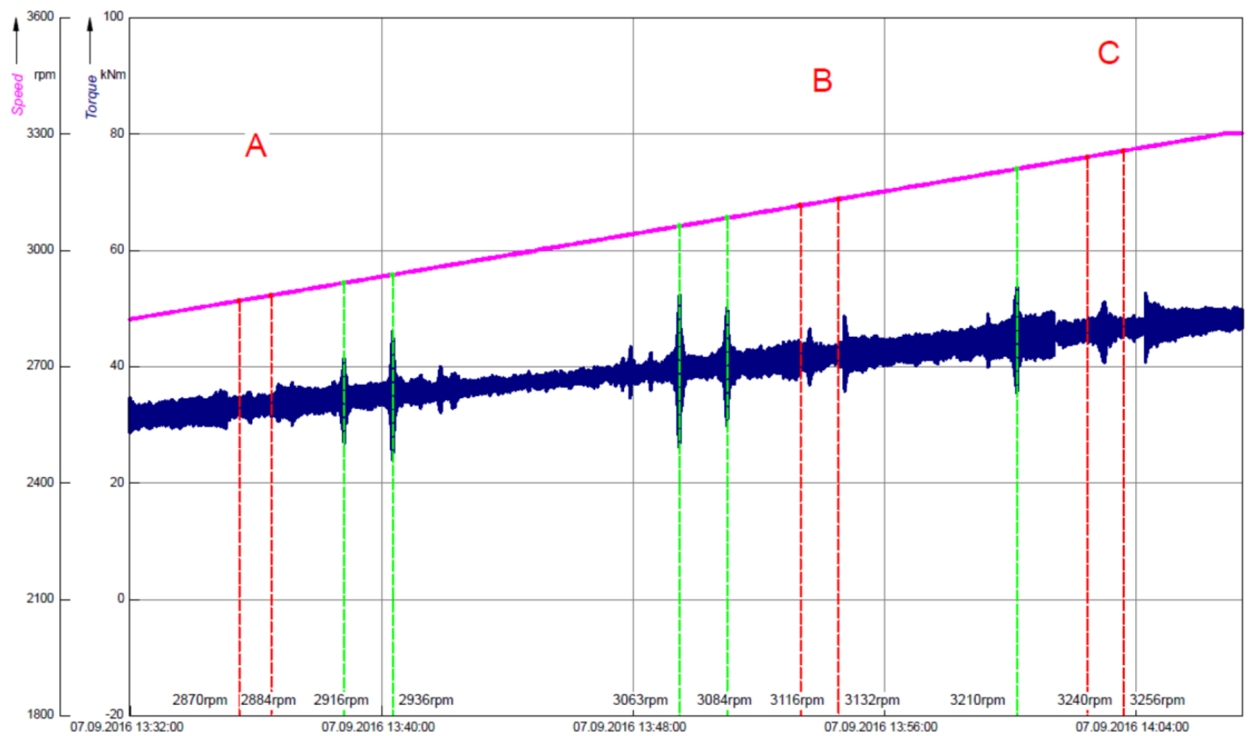

Figure 18: Measured speed and torque at the low speed side with active interharmonic damping

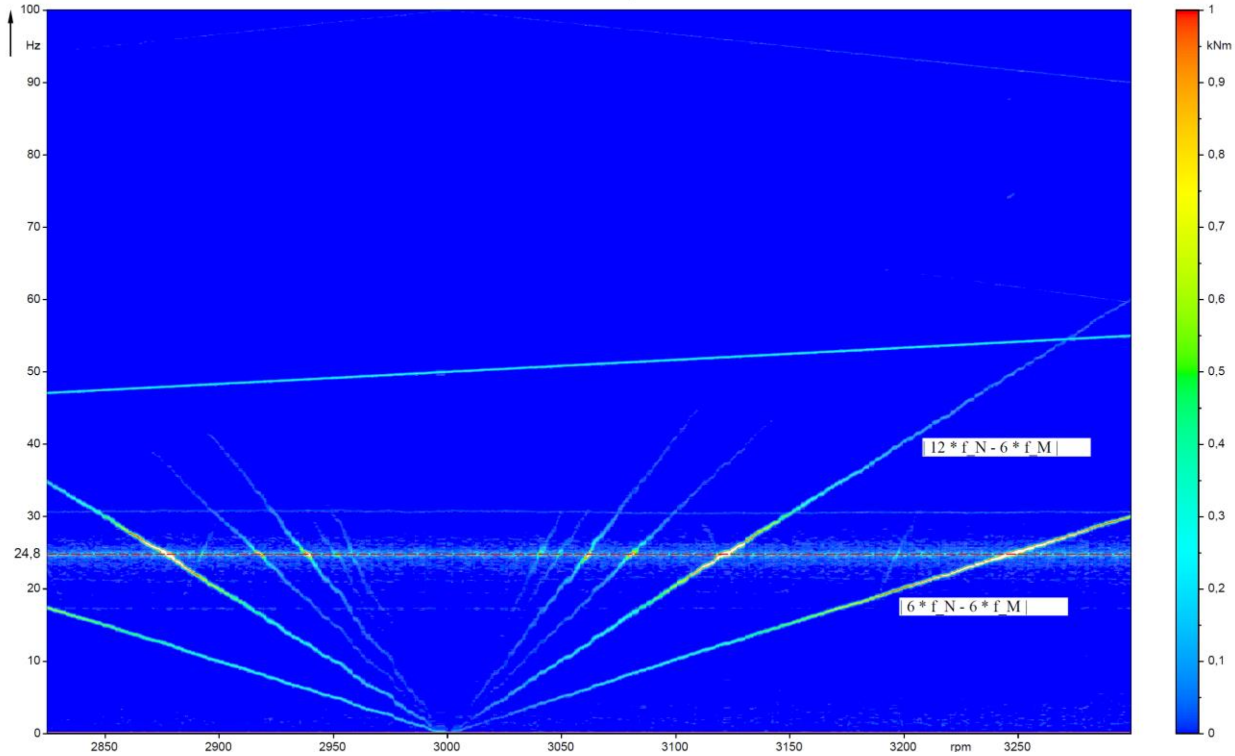

Figure 19: Waterfall diagram of measured torque over the operating speed range without the active interharmonic damping.

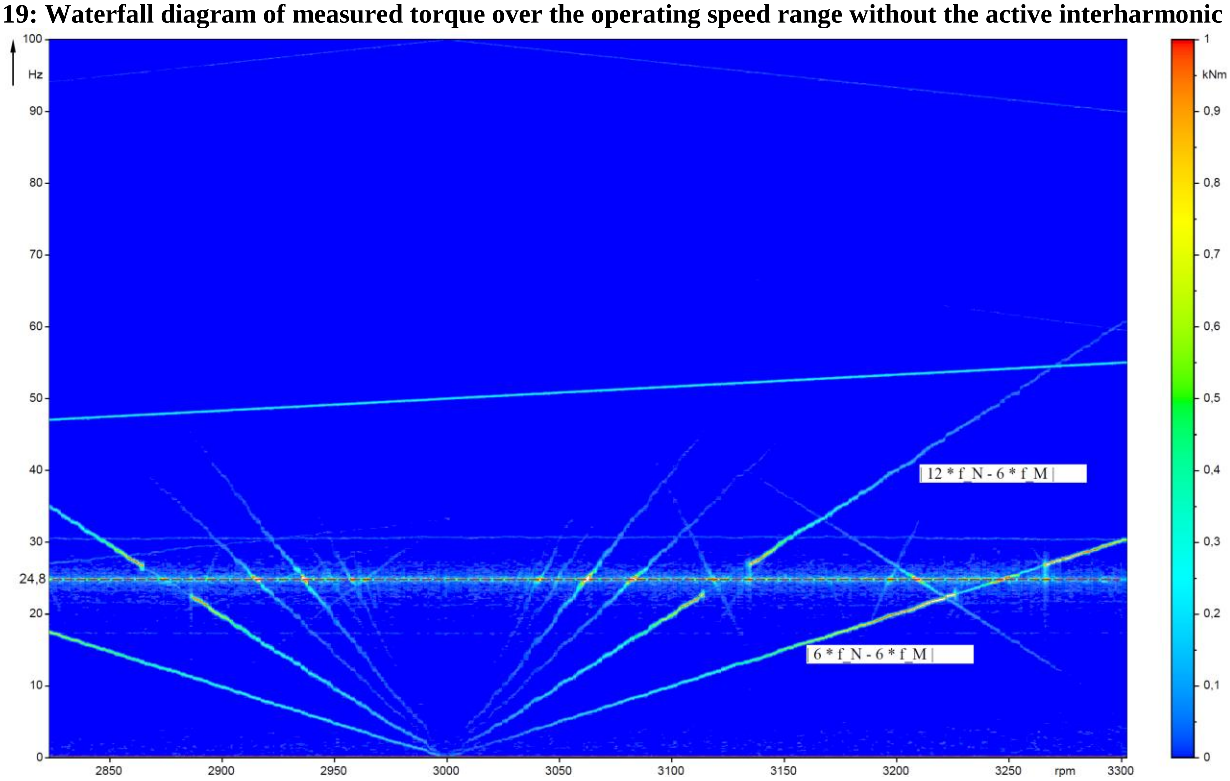

Figure 20: Waterfall diagram of measured torque over the operating speed range with active interharmonic damping.

CONCLUSIONS

This paper explains the torsional oscillation problem related to the turbo compressor drive train. The air-gap torque excitations due to the VFDs are introduced. The principle of LCI drive system and their injected interharmonic air-gap torque excitations are explained. A novel active interharmonic damping technique which is realized in the drive control software is proposed and its basic principle has been presented. The effectiveness of the proposed interharmonic damping technique has been demonstrated through real time measurements at a suitable plant.

ABBREVIATIONS

VSDS = Variable Speed Drive System
VFDs = Variable-frequency drives
MV = Medium voltage
LV = Low voltage
LCI = Load Commutated Inverter
CSI = Current source inverter
VSI = Voltage source inverter
DC = Direct current
AC = Alternating current
TNF = Torsional Natural Frequency
OEMs = Original equipment manufacturers

SYMBOLS

J = Moment of inertia in kgm^2
C = Stiffness in Nm / Rad
f_{grid} = Grid supply frequency in Hz
f_{motor} = Motor electrical frequency in Hz
n_{motor} = Motor speed in rpm
i_{DC} = DC-Link current in A
v_{DC} = DC-Link voltage in V
f_{h_Torque} = Harmonic frequency component in air-gap torque in Hz
$f_{h\_Current}$ = Harmonic frequency component in motor current in Hz
f_{1_Motor} = Fundamental motor (electrical) frequency in Hz
$N_{PolePairs}$ = Number of pole pairs of the motor
F_{TNFs} = Critical torsional natural frequencies in Hz
ΔF = Frequency band around the specified TNFs for active damping in Hz
Tact = Actual air-gap torque in Nm
i_{in} = measured input current in A
v_{in} = measured input voltage in V
i_m = measured motor current in A
v_m = measured motor voltage in V
α_{mot} = firing angle for motor side inverter thyristors in °
α_{motIH} = firing angle correction for motor side inverter thyristors in °

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